The Determination of the Location of Contact Electrification-Induced Discharge Events

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Abstract

This paper describes a method for determining the location of contact electrification-induced electrical discharges detected in a system comprising a steel sphere rolling in a circular path on an organic insulator. The electrode of the "Rolling Sphere Tool" (RST), monitors, in real time, the separation of charge between the sphere and the organic insulator, and the resultant electrostatic discharges. For every revolution of the sphere, the electrometer records a peak, the height of which represents the amount of charge on the sphere. As the charge on the sphere accumulates, the resulting electric field at the surface of the sphere eventually exceeds the breakdown limit of air and causes a discharge. The position of this discharge can be inferred from the relative amplitudes and positions of the peaks preceding and following the discharge event. We can localize each discharge event to one of several zones, each of which corresponds to a geometrically defined fraction of the circular path of the sphere. The fraction of charge on the sphere that could be detected by the electrode depended on the relative positions of the sphere and the electrode. The use of multiple electrodes improved the accuracy of the method in localizing discharge events, and extended the range of angles over which they could be localized to cover the entire circular path followed by the sphere.

Keywords: (Contact Electrification, Tribocharging, Electrostatic Discharge)

Introduction

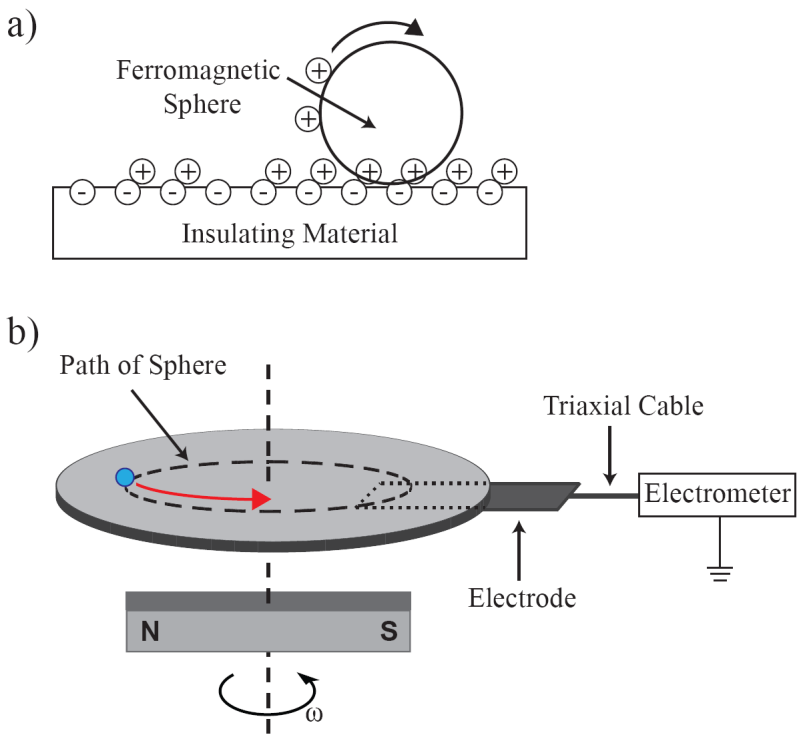
Contact electrification —the transfer of charge between two objects when they are brought into contact and then separated— is ubiquitous;[1,2] even two pieces of identical material brought into contact can result in charge separation.[3-9] The phenomenon of contact electrification has been known for thousands of years[10] and has been exploited in

many ways including x-ray generation,[11] xerography,[12] and electrostatic separation.[13] A detailed understanding of the fundamental mechanism of contact electrification, however, has remained elusive. For example, contact electrification is often associated with friction ("rubbing a plastic comb with a silk scarf"); it is, however, presently unclear whether there are important differences between electrification with and without friction, or whether friction is incidental to the pressures required to bring surfaces into intimate contact.[14]

The most significant result of contact electrification is the charge that develops on the participating surfaces. The amount of charge is dictated by the interplay between two counteracting processes: charging and discharging. With insulators, the former refers to the slow accumulation of charge by transfer of ions (and/or other charge carriers) from one surface to another (Figure 1a), and the latter is the rapid, localized discharge (probably mediated by a plasma or corona) between the two surfaces when the accumulated electric field exceeds the breakdown limit of the surrounding media (often air).[15]

Charging. The mechanism of charging between different classes of materials is still incompletely understood, and is the subject of active debate.[16-22] Two mechanisms have been proposed for charge transfer between different materials: i) electron transfer, and ii) ion transfer. Contact charging between conductors or semiconductors certainly can occur by electron transfer; these materials have mobile electrons and well-defined Fermi levels.[2] (The existence of a plausible mechanism for electron transfer does not, however, preclude charging by ion transfer.) In the earlier physics literature, many discussions

Figure 1. a) Schematic illustration of a steel sphere rolling on a surface functionalized with covalently bound negative ions and mobile positive counter ions; the mobile cations transfer to the sphere during contact electrification. b) Illustration of the Rolling Sphere Tool (RST) that measures the dynamics of contact electrification and electrical discharge. The RST system consists of a ferromagnetic sphere that rolls (not slides) in a circular path on an insulating material under the influence of a rotating magnet located below the surface. As the sphere rolls on the surface, charge separation occurs; an electrode located directly below a portion of the insulating material, and connected to an electrometer, records charge separation in real time.



concerning charging of insulating materials have, however, assumed without (so far as we can see) any compelling experimental evidence that electron transfer is involved, even though there are neither plausible electron donors nor plausible acceptors in insulating organic solids. In any event, if free electrons were generated (as we believe they are during discharge events) they would attach themselves to molecules and form ions. In fact, Putterman *et al.* proposed that x-rays generated by the peeling of tape at reduced pressure were caused by electrons from electrostatic discharges that struck the positively charged adhesive.[11,23] While some efforts to support the hypothesis of electron transfer (with data from an organic insulator in contact with a metal) have shown a correlation between surface charge density and work function of a metal,[24] others have shown that there is no correlation.[25] Bard and co-workers[17,18,26] have recently shown that vigorous rubbing of Teflon against, for example, poly(methylmethacrylate) (PMMA) induced apparent redox reactions (e.g. metal-ion reduction) on the surface of the charged Teflon when it was submersed in aqueous solutions containing appropriate redox agents. Based on these observations, they have suggested the involvement of something they call a "cryptoelectron" in contact electrification. It is, however, not clear what a "cryptoelectron" might be – the only possibilities for carriers of charge are electrons or ions. Gryzbowski and co-workers proposed an entirely different interpretation for similar phenomena. They attributed the reduction of metal ions and the bleaching of dyes by PDMS (charged both negatively and positively by contact electrification) to radicals generated by mechanical deformation on the surface of the polymers.[27,28]

Diaz and co-workers[29] proposed an ion-transfer mechanism for charge separation involving insulators. They investigated ionomers, a class of polymers with charges

covalently bound to the polymer chain and unbound counter charges. These polymers would develop charge of the same sign as the covalently bound ion, whereas the contacting metal would develop the charge of the mobile counterion (Figure 1a). In previous work,[30] we showed that the agitation of microspheres functionalized with covalently bound, positively charged groups (with mobile negative counterions) developed a positive charge when they charged by contact electrification against an aluminum dish. Conversely, the agitation of microspheres functionalized with covalently bound, negatively charged groups (with mobile positive counterions) charged negatively by contact electrification against an aluminum dish. More recently, we reported similar results for glass silanized with charged, self-assembled monolayers.[31] All of these observations are consistent with the ion-transfer mechanism of charge separation for organic insulators.

Discharging. Unlike charging, discharging is sudden (~10 ns)[32] and quasi-periodic. As charge on an object slowly accumulates due to contact electrification, so does the associated electric field. A discharge happens when this field exceeds a threshold, which is largely dictated by the dielectric strength[33] of the surrounding medium. Electrical discharge can be as powerful as lightning during thunderstorms or as trivial as sparking when touching a doorknob with a dry hand; the magnitude of the discharge depends mostly on the amount of charge transferred during the process. The factors that influence discharging are not well understood and are also the subject of active research.[34,35]

Electrical discharges due to triboelectrification are estimated to cause billions of dollars in damages in the US each year[36,37] in the forms of, for example, damage to

electronic equipment,[38] and ignition of combustible materials that cause damage by explosions.[39] Understanding the factors that influence the probability of discharge will contribute to a fundamental understanding of the charging and discharging that characterize contact electrification, as well as to the development of strategies to control the likelihood and/or location of discharges, and thus to minimize the risk of sparking.

Rolling sphere tool. One of the difficulties in studying contact electrification, both charging and discharging, has been the lack of a reliable experimental system that can generate highly reproducible results. Grzybowski *et al.* first described a system that has proved exceptionally useful in studying tribocharging—the "Rolling Sphere Tool" (RST) (Figure 1b).[40-42] This experimentally convenient system comprises a ferromagnetic steel sphere rolling (not sliding) on an insulating surface under the influence of a magnet rotating *under* the surface (with no direct, physical contact to it). The sphere follows a circular path on this surface. We have exploited the RST to study different aspects of contact electrification including: the mechanism and kinetics of charge separation,[40,41] the patterns of electrostatic charging and discharging,[31] strategies to control charging due to contact electrification,[43] and the dynamic self-assembly of charged spheres.[44] More recently, Thomas and Friedle used the RST to demonstrate control over charging behavior using photochromic polymers.[45]

This paper focuses on electrostatic discharge, the lesser studied phenomenon related to contact electrification. In a previous paper, we showed that the RST can reliably produce a large number of discharge events.[31] Here we describe a method that we developed to determine the location of each individual discharge event. This method allowed us to perform statistical analysis on the positional distribution of discharges. In

particular, we show that air plasma treatment of a surface can greatly influence the probability of discharge, and that if only a portion of surface was treated, we can locate that region using our method.

Experimental Design

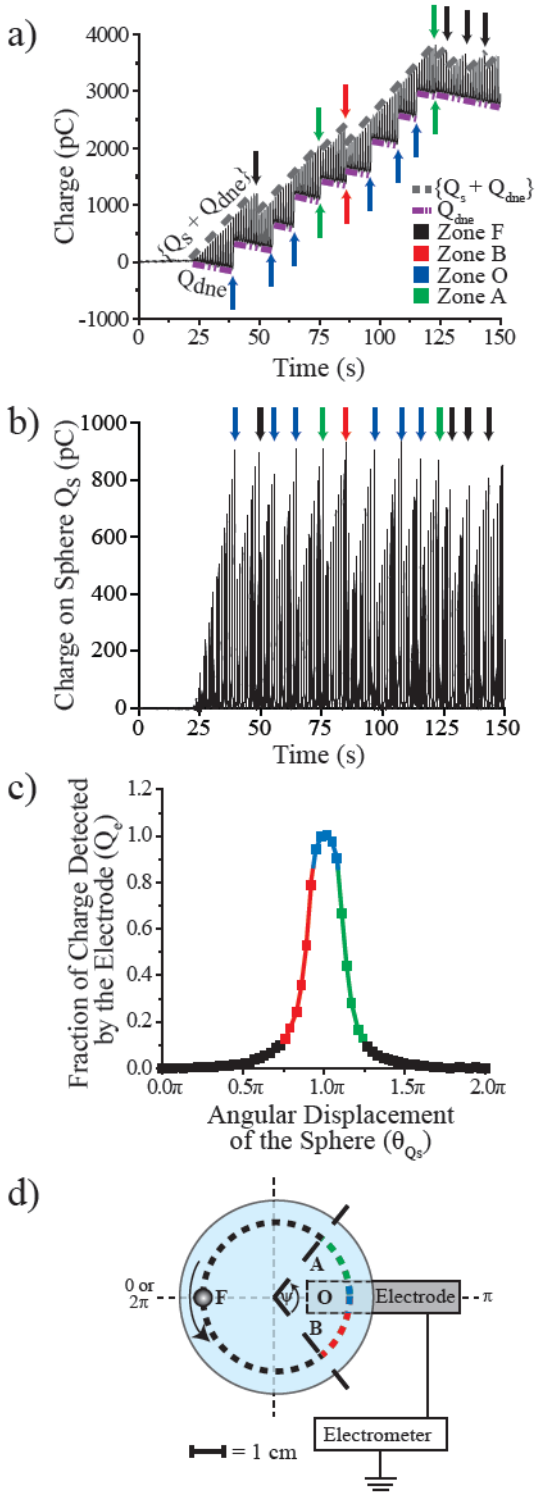
The RST (Figure 1b) consists of a rotating permanent magnet, located below a disk made of an organic insulator (or any other dielectric material), the magnetic field of which causes a ferromagnetic stainless steel sphere to roll in a circular path on the disk.[44] An electrode located directly *beneath* the disk, connected to an electrometer, senses charge inductively in real time.

Figure 2 plots the accumulation of the charge measured by the electrometer in time; the measured charge consists of two parts: the charge on the *sphere* (Q_s) and the charge on the portion of the *disk that is near the electrode* (Q_{dne}) and close enough for it to be inductively coupled to the electrode. Peaks in the data occurred when the sphere was directly above the electrode; for these peaks, the electrometer measured the sum of the charge on the sphere and the portion of the disk near the electrode ($\{Q_s + Q_{dne}\}$). Valleys occurred when the sphere was far from the electrode; at the floor of these valleys, the electrometer measured only the charge on the portion of the disk that the electrode sensed (Q_{dne}).

Charge separation between the sphere and the disk produced a potential difference that eventually lead to electrical discharge. In Figure 2, each discharge event corresponds to a sharp disruption in the trend-lines characterizing the data (e.g. those indicated by arrows). These disruptions are manifested by sudden decreases in the heights of the peaks

Figure 2. a) Experimental data showing the charge sensed by the electrode during contact electrification of a steel sphere (d = 3.2 mm) rolling on a glass disk (T ~ 25 °C, RH < 10%). The width of the electrode (w) was 10 mm (0.13π radians), and the circumference of the circle traced by the sphere was ~ 150 mm. Electrical discharge events (indicated by arrows) interrupted the linear accumulation of charge, in the baseline (which represents the charge on the area of the disk close to the electrode) [Q_{dne}, purple (–··–)] and/or in the peaks (which represent the sum of net charge on the sphere and the surface of the glass disk near the electrode) [{$Q_s + Q_{dne}$}, (---)], or a combination of both. Blue arrows indicate discharges that occurred close to or over the electrode; black arrows indicate discharges that occurred sufficiently far from the electrode that the electrode did not sense them; red arrows indicate those that occurred just before the sphere rolled over the electrode; green arrows indicate those just after the sphere left the electrode (*vide infra*). b) Processed data showing only Q_s (= {$Q_s + Q_{dne}$}– Q_{dne}) sensed by the electrode. The colored arrows correspond to the same discharges shown in (a). c) A plot of Q_s over one period (one revolution of a steel sphere rolling on a poly(styrene) (PS) Petri dish). Q_s = {$Q_s + Q_{dne}$} – Q_{dne}, and was normalized to 1. The curve represents the fraction of charge that the electrode detected (black segment: 0-0.1, red and green segments: 0.1-0.9, blue segment: 0.9-1.0) as a function of the position of the sphere relative to the center of the electrode (width, w = 1.0 cm); we assigned the center of the electrode to be π radians. d) The circular path of sphere was divided into four detection zones: Zone **F** – the sphere is *far* from the electrode (black); Zone **B** – the sphere is near the electrode, approaching it (*before* the electrode) (red); Zone **O** – the sphere is directly *over* the electrode (blue); Zone **A** – the sphere is near the electrode, moving away from it (*after* the electrode)

(green). Each zone corresponds to the colored segment in (c). The arrow indicates the direction in which the sphere rolled.



($\Delta\{Q_s + Q_{dne}\}$), or by sudden increases in the baseline (ΔQ_{dne}), or by a combination of both.

Processing the data by subtracting Q_{dne} from $\{Q_s + Q_{dne}\}$ (Eq. 1) generated a plot that showed only Q_s sensed by the electrode versus time (Figure 2b). From these data, we

$$Q_s = \{Q_s + Q_{dne}\} - Q_{dne} \quad (1)$$

obtained the maximum amount of charge on the sphere before and after each discharge. The difference between them (ΔQ_s) gave the total amount of charge transferred during a discharge (Eq. 2).

$$\Delta Q_s = Q_s \text{ (before discharge)} - Q_s \text{ (after discharge)} \quad (2)$$

Table 1 summarizes the variables (and their meanings) that appear throughout the paper.

The average maximal charge on a steel sphere (d = 3.2 mm) rolling on plasma-oxidized poly(styrene) before discharge in air was 1250 ± 380 pC. This value is on the same order of magnitude as the value of 940 ± 60 pC determined from a steel sphere of the same size rolling on clean glass.[31] The electric field at the surface of an isolated sphere is given by Eq. 3:

$$\vec{E} = \frac{Q}{4\pi\varepsilon_o r^2} \quad (3)$$

A steel sphere (r = 1.6 mm) with a charge of 1250 pC has an electric field of ~44 kV/cm at its surface; this value is close to the dielectric strength of air (~30 kV/cm at 1 atm of pressure). Our earlier results also showed that the maximal charge that accumulated on the steel sphere before discharge correlated with the dielectric strength of the surrounding gas.[31]